Soil Stabilisation with Ground Granulated Blastfurnace Slag

by Dr D D Higgins

UK Cementitious Slag Makers Association (CSMA)
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SUMMARY

This report summarises UK research and practical experience relating to the use of ggbs+lime[1] combinations for soil stabilisation. Laboratory research and field trials have confirmed that sulfides, as well as sulfates, are liable to cause disruptive expansion in stabilised soils. It has been shown that ggbs+lime combinations are practical and effective options for soil stabilisation, and provide technical benefits. In particular the incorporation of ggbs, is very effective at combating the expansion associated with the presence of sulfate or sulfide in soil. Following the extensive program of research and site trials, lime+ggbs stabilisation is now an established technique in the UK and is becoming a preferred option where there are sulfates or sulfides present in the soil.

1. INTRODUCTION

Ground granulated blastfurnace slag (ggbs) is readily available throughout the UK. Its main use is in concrete and most readymixed concrete plants have a silo of ggbs, which they use to 'replace between 40 and 70% of Portland cement. The UK uses 2 million tonnes of ggbs per annum (cf. 12.5 mtpa of cement). On its own, ggbs has only slow cementitious properties and Portland cement normally provides the alkalinity to activate and accelerate these properties. Lime can also be used to provide the necessary alkali for activation and indeed the original blastfurnace cements produced in Germany in the late 1800's were mixtures of lime and blastfurnace slag. Further information on the production and use of ggbs is given in Appendix '1'.

Soil stabilisation is widely used in connection with road, pavement and foundation construction. It improves the engineering properties of the soil, e.g.:

- strength - to increase the strength and bearing capacity,
- volume stability - to control the swell-shrink characteristics caused by moisture changes,
- durability - to increase the resistance to erosion, weathering or traffic loading.

Normally, lime or cement (or a combination) is used for soil stabilisation. The principles and practices are well documented [1,2,3,4].

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[1] In this report 'lime' is used as a general term covering either quicklime [CaO] or slaked lime [$Ca(OH)_2$]

In South Africa, ggbs activated by lime, is a commonly used binder for soil stabilisation [1,5] and there is 40 years experience of its use [6]. Blends of lime and ggbs are frequently used in Australia, where the slower initial set and increased time for finishing, compared with using Portland cement [7,8], is preferred by many of the stabilisation contractors. Prompted by the Southern Hemisphere experiences, the CSMA decided to investigate the potential of lime+ggbs for use in soil stabilisation in the UK. These investigations included extensive research at a University and several full-scale site trials.

In 1995, the CSMA initiated a major research program at the University of Glamorgan, related to the stabilisation of soils with lime+ggbs. The University investigated the full range of properties relevant to stabilisation, e.g. strength, swelling, permeability, initial lime consumption, plastic limit, liquid limit and optimum moisture content. Detailed records can be found in relevant Doctorate Theses [9,10,11] and in published papers [12,13,14,15,16,19,20,21].

A main focus of the research was 'sulfate-expansion'. The presence of sulfates can cause serious problems of swelling and heave of stabilised clay [22,23,24,25] and this 'sulfate' swelling has been linked with the formation of ettringite. In concrete construction, it is well established that cements containing ggbs are resistant to the expansion and swelling caused by ettringite formation. For example, 'Supersulfated Cement' is made by blending 80 to 85% of ggbs with 10 to15% of calcium sulfate and about 10% Portland cement or lime, is included as an activator. Although ettringite is a principal hydration product and a substantial amount of sulfate is present in the system, the cement has no tendency to expand [26]. It is also highly resistant to attack by external sulfates. This, together with the well-established sulfate-resisting properties imparted to Portland cement by blending with ggbs [26], suggested that blends of lime and ggbs might be resistant to swelling caused by sulfate. The research quickly demonstrated a significant advantage of ggbs over conventional lime or cement stabilisation, with ggbs being very effective in counteracting the swelling that can occur when sulfate-containing clays are stabilised conventionally, with cement or lime.

In parallel with the University research, site trials were carried out by specialist soil stabilisation contractors. Separate application of the lime and the ggbs was chosen to mirror the common practice where lime is added initially to sticky soils to 'modify' and break them down before attempting stabilisation with cement. All the trials were complete successes. Using standard plant and techniques, the contractors experienced no difficulties in carrying out the stabilisation. Subsequent tests on the stabilised soils confirmed that satisfactory density and strength had been achieved. Comparison with a control areas stabilised using lime + Portland cement, suggested that the use of ggbs gave enhanced long-term strength and combated sulfate heave.

Following the program of research and site trials, lime/ggbs stabilisation of soils has become an established technique in the UK and is a preferred option where there are sulfates present in the soil [27].

2. SUMMARY OF RESEARCH AT GLAMORGAN UNIVERSITY

Most of this research has been formally reported and abstracts from selected papers are reproduced in Appendix 1.

It was found [9] that ggbs had only minor effects on

- initial lime consumption
- Atterberg limits (i.e. liquid limit, plastic limit and plasticity index)
- optimum moisture content

For these properties, the ggbs was relatively 'inert' and the effect of the lime was predominant.

There was some evidence that ggbs reduced the permeability of the stabilised clay [10,12]

The effect on compressive strength, of varying the total stabiliser content, together with the proportions of lime, ggbs and gypsum was investigated [9,10,11,12,13,14,16]. It was found that inclusion of ggbs can markedly increase the compressive strength of stabilised clays, relative to that achieved by lime-only. The gypsum content also had a significant effect on strength development and the precise relationship between strength and the composition was complex. This was attributed to interactive effects between the lime, ggbs and gypsum (each can react with the others).

Much of the University research concentrated on sulfate-expansion. Typical results are shown in Figure 1.

Figure 1: Suppression of swelling by ggbs

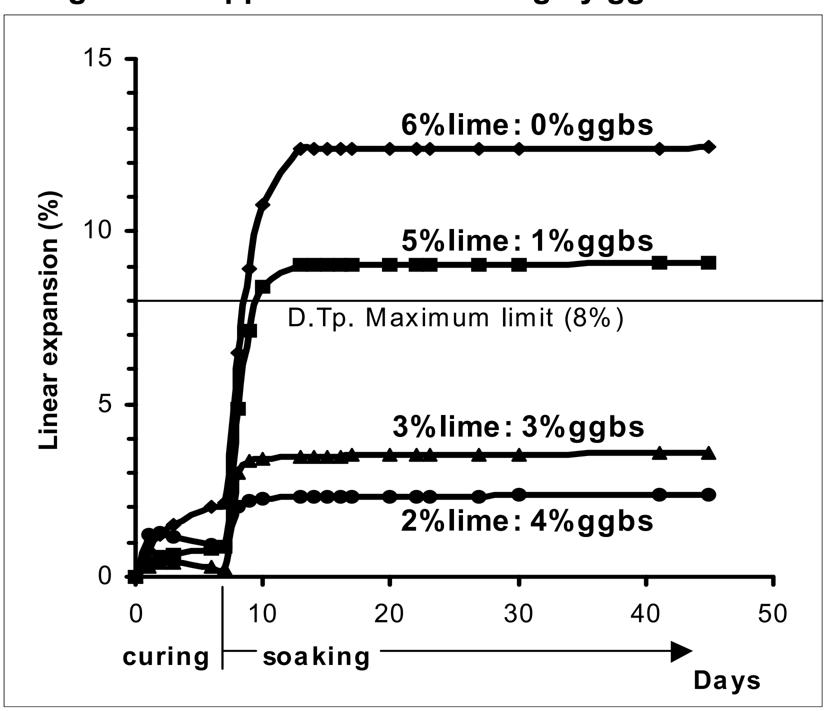


Figure 1 plots the expansion of clay specimens, stabilised with various percentages of lime and ggbs [16]. In this case, the 'clay' was Kaolinite, which had gypsum 'artificially' added to give 2.8% SO_3, by weight of 'clay'. After mixing with lime+ggbs, cylindrical specimens were moulded and initially cured at high-humidity for 7-days, before being soaked in water. The specimen stabilised with lime-alone shows high expansion, in contrast to those stabilised with combinations containing high proportions of ggbs, which exhibit low expansions. Similar reductions in expansion were obtained with a Kimmeridge clay, which naturally contained 1.7% SO_3 [16].

Having established the effectiveness of ggbs in combating expansion in the presence of sulfates, investigations then concentrated on the effects of the presence of sulfide in stabilised soil. It is well established that sulfide in soil has the potential to oxidise to sulfate and cases of sulfate disruption have been associated with pyrite (iron sulfide) [2,24]. However, there was little information available on the rate and extent to which sulfide oxidises in stabilised soil. A review of 'chemical literature' suggested that the elevated pH produced by addition of lime (or cement) might greatly increase the propensity to oxidise to sulfate. Cassanova & al [17,18] have considered pyrite oxidation over a wide pH range and conclude that it is highly pH-dependent. They demonstrate from thermodynamic considerations, that no iron sulfide will be stable above a pH of 10 and refer to experimental evidence that the speed of oxidation is greatly enhanced under strongly alkaline conditions ($12.5<pH<13.7$), the rate increasing 50 times for every 1.2 increase in pH.

Investigations into the effect of sulfide, used a Lower Oxford Clay, chosen because it had a low sulfate content of 0.6%, but a high sulfide content (see Table 1).

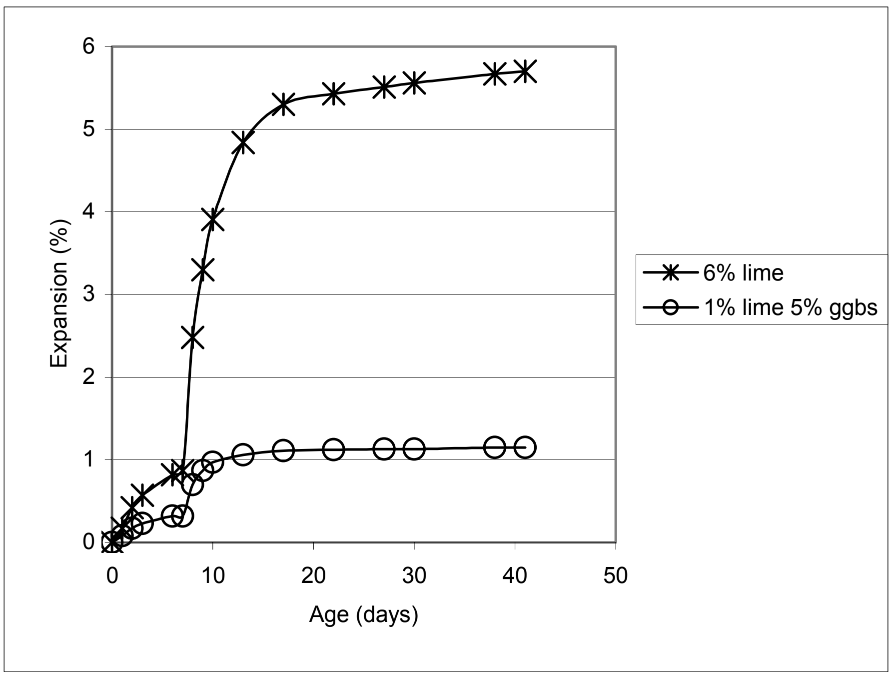
Table 1. Typical sulfate analysis of Lower Oxford Clay used in studies

Component	S (% sulfur by mass)	equivalent SO_3 by mass
Sulfur present as sulfate	0.24	0.60
Sulfur present as pyrite	0.64	1.60
Total sulfur by BS 1047	2.5	6.25
Sulfur deriving from organic and other sources (by subtraction)	1.6	4.05

Lime-stabilised specimens of this clay (without ggbs) expanded rapidly, within the first few days of soaking and the expansion was much greater than would have been expected with the 0.6% sulfate content of the clay [19]. This indicated that oxidation of sulfide to sulfate had occurred. Chemical analysis was employed to measure the rate of oxidation of the sulfide in this clay [19]. In 'virgin' specimens where no lime was added, no oxidation was detected. However, specimens to which lime had been added, showed large increases in SO_3 content. The SO_3 content roughly doubled during the 7-day moist curing period and was 3 or 4 times greater after a further 14 days of soaking. This occurred under laboratory conditions where there was only limited exposure to the atmosphere. It was concluded that the increase in pH that occurs when soils are stabilised with lime or cement, will inherently promote rapid oxidation of sulfide to sulfate. Consequently sulfides must be considered equally with sulfates, as a potential for sulfate disruption.

Inclusion of ggbs was equally effective at suppressed expansion with the clay containing sulfide as it had been with clays containing sulfate. Figure 2 [19] shows the linear expansion versus the soaking time, for the Lower Oxford Clay stabilised with 6% lime compared with the same clay stabilised with 1% lime + 5% ggbs. The specimens containing ggbs showed only minimal expansion (1%), whereas the lime-stabilised specimens expanded by about 5.5%.

Figure 2. Effects of pyrite oxidation on expansion of stabilised Lower Oxford clay



In addition to investigating the effects of ‘internal’ sulfate and sulfide in the soil, the research also looked at the effects of soaking stabilised clay in 4.2% Na_2S0_4 solution [20]. This simulated the situation where stabilised soil was exposed to sulfates from external groundwater. The test data showed that inclusion of ggbs ‘dramatically’ reduced expansion under exposure to sulfate solutions.

Scanning electron microscopy and X-ray diffraction studies were employed to investigate the mechanisms by which ggbs combats expansion [21]. Specimens of lime-stabilised kaolinite with different percentages of lime replacement by ggbs, were exposed to sulfate. It was found that the replacement of lime by ggbs resulted in a progressive modification of the ettringite morphology. Three different growth mechanisms of ettringite were observed, namely (a) well-formed randomly orientated rods of high aspect ratio growing in pores and cracks, (b) short needles covering surfaces of existing particles and (c) 'flower-like' needles radiating from isolated points and scattered randomly through the sample. The potential for water absorption appears to be dependent on the composition of the ettringite and in particular on its calcium content. It was postulated that the inclusion of ggbs reduces the relative calcium content of the ettringite and the potential for swelling.

The research also investigated alternatives to ggbs, for reducing sulfate expansion. The US National Lime Association suggest that a mellowing period between the addition of lime and final compaction, can reduce sulfate expansion [28], because sulfate reaction that is encouraged to occur before compaction, will not cause disruptive expansion of the compacted layer. The effect of mellowing was investigated for lime-stabilised Lower Oxford Clay, using only lime as the binder [29]. Whereas, mellowing at 5^{o}C for 3 days, did not reduce expansion, mellowing at 20^{o}C for 3 days did produce some reduction in expansion, typically reducing expansion to ¾ of the unmellowed value. However, any benefits of mellowing were much less than could be achieved by adding ggbs. The Lower Oxford clay used in these tests contained sulfide, and it is likely that oxidation would have continued to create ‘new’ sulfate after the mellowing period. Had the clay only contained sulfate, the results for a mellowing period with lime-only, might have been more encouraging.

3. SUMMARY OF SITE TRIALS

The first trial formed part of the construction of a distribution warehouse [30,31]. Here, the sub-base for concrete hardstanding was an insitu ‘silty/clayey sand’, stabilised with 9% cement. For a test area of 500m^2 in the lorry loading area, 2% lime+8% ggbs was used, instead of cement. The stabilising contractor experienced no difficulty in carrying out the ggbs stabilisation. Satisfactory density and strength were achieved. At 7-days cube strengths for the ggbs area were typically 2N/mm^2 compared with 3N/mm^2 for the cement area. At 28-days the ggbs strengths had exceeded those for cement and by 90 days had attained 6N/mm^2.

The second trial was carried out as part of the construction of the Tingewick Bypass [32]. A temporary diversion was needed to carry the A421 traffic. This soil on this site was a boulder clay, containing sulfate and sulfide, which provided an opportunity to evaluate lime+ggbs stabilisation in the presence of sulfate/sulfide. The temporary diversion comprised a sub-base of the boulder clay stabilised with lime+ggbs, which was overlaid with 130mm of bituminous surfacing. Trial areas were laid with 1.5% quicklime+ 6.5% ggbs, 1.5% quicklime+ 8.5% ggbs and 1.5% quicklime+ 8.5% cement. Using standard plant and techniques the contractor experienced no difficulties and satisfactory density and strengths were achieved. Because of delays with the main contract, the temporary diversion carried the full A421 traffic for just over a year, providing an extended performance test. The temporary diversion performed well over this period. No disruption attributable to sulfate expansion was observed on the lime+ggbs sections but there were indications of expansion at the end of the short lime+cement section. Before stabilisation, the measured sulfate levels in the clay were low. 15 months after stabilisation, cores were drilled out of the stabilised clay and several of these from each section were analysed for sulfate and total sulfur. At the same time, some samples of equal age, taken immediately following stabilisation but subsequently stored in the laboratory, were also analysed. After 15 months, the sulfate level was at a high level of about 1.0% of sulfate throughout the trial area. Similar but slightly lower levels were found in the laboratory-stored samples. It was concluded that there had been substantial oxidation of the sulfide initially present, both on-site and in samples taken at the time of construction and subsequently stored in the laboratory. This had produced a high level of sulfate, apparently sufficient to cause disruption at the end of the lime+cement section, but no disruptive expansion occurred in the lime+ggbs sections.

A third trial of about 500m^2 was carried out, but has not been formally reported. On the car parking areas for a hospital, 26,000m^2 of soil was stabilised using '2 % lime+ 2.5%' cement as sub-base and capping under bituminous surfacing. As a comparative trial, the contractor agreed to treat an area using ggbs as a straight replacement for the PC. With the ggbs, CBR values were "very satisfactory" (~ 100% at 5-days).

We understand that a further trial area of 150 x 20m using lime+ggbs, has been constructed for the Highways Agency, on the A6 Higham Ferris Bypass near Bedford. Sulfate was present in the clay and this trial will be monitored long-term.

4. FULL SCALE APPLICATIONS

The following table lists details of soil stabilisation contracts, carried out using ggbs.

Location	**Soil type**	**Stabilised with**	**Date**	**Ggbs used (tonnes)**	**Comments**
Dartford	silt?	ggbs/PC	1985	422	Stabilisation carried out as part of the reclamation of Stone Marshes.
Baddersley Colliery	colliery shale	ggbs/ PC in ratio: 70:30	Nov 1998	674	Area of 140,000m^2 of colliery shale, stabilised to form a car storage area . Ggbs used because of the presence of sulfates and sulfide.
Northampton	?	ggbs/CaO	Feb 1999	408	Distribution depot
Bedford.	?	ggbs/ CaO	Nov '99 to Jan 2000	676	Distribution depot
Chelmsford A130 1km	sulfate-bearing clay	4% ggbs/ 2% CaO	May to Nov 2000	571	Sub-base for Trunk road .
Chelmsford A130 approx 5km			Jun to Aug 2001	2,279	
Chelmsford A130 2nd phase			Apr to Sep 2002	1,606	
Silverstone Racetrack	Sandy Gravely boulder clay	6% ggbs/ 2% CaO	Feb to Apr 2002	1,726	55,000m^2 stabilised as capping layer, for car parking areas at Silverstone Racetrack. Ggbs used because of the presence of sulfates. [33]
West Norwood	London clay	4% ggbs/ 2% lime	May 2002	275	6,000m3 of bulk fill material was stabilised to form platform for building
A6 Clapham Bypass	boulder clay containing sulfate	* % ggbs/ * % CaO	Jun to Jul 2002	401	New section of A6 to by-pass Clapham nr Bedford. Stabilised soil used as capping layer
Baldock Bypass	Glacial Till	* % ggbs/ * % CaO	Nov 2004	400	Sub-base for Bypass
	Chalk	* % ggbs/ * % CaO	2005	1,619	
Huddersfield	colliery spoil	6% ggbs/ 2% CaO	2005	264	10.000m^2 site for Business Park was stabilised [34] Ggbs used because of the presence of sulfates and sulfide.
Tamworth	gravelly clay	4% ggbs/ 2% lime	April 2005	144	Sub-base for service yard
Redditch	?	ggbs/ CaO	July 2005	176	
Rushden	Glacial Till containing sulfate	3% ggbs/ 2% CaO	July 2005	493	Sub-base for building, adjacent service yard and car-parking
* percentages not authorised for public release					

5. PROPORTIONING OF GGBS vs LIME

Resistance to sulfate expansion increases with the ratio of ggbs to lime. While significant resistance can be achieved with a ggbs:lime ratio of 1:1, the greatest resistance was found at high ggbs:lime ratios, typically 5:1 or greater. The Tingewick trial [32] demonstrated the practicality of using a ggbs:quicklime ratio as high as 5.7:1 but the 'Applications' listed in section '4' used a more restricted range of ggbs:quicklime ratios, between 1:1 and 3:1.

In Australia, a commonly used blend is 85%ggbs/15% hydrated lime [7,8]. This would equate to a ggbs:quicklime ratio of 7.4:1. However it should be noted that Australian practice differs from that in the UK, in that the ggbs and lime are pre-blended rather than being added to the soil in separate operations. South African practice replicates the UK with a 2-stage addition and South African Specifications [6,35] suggest a ggbs: hydrated-lime ratio of 4:1 as the 'optimum proportions'. This corresponds to a ggbs:quicklime ratio of 5.2:1 and because ggbs is not used for sulfate-resistance in South Africa, 'optimum' would presumably be optimum for strength.

For UK applications, quicklime is normally used and an initial application of at least 1.5% of quicklime (by weight of soil) will generally be necessary to modify the clay and provide sufficient alkalinity to activate the ggbs. Where the ggbs is being used for enhanced resistance to sulfate expansion, the proportion of ggbs should sensibly be at least equal to that of the quicklime and typically for high resistance to sulfate expansion, a ratio of 3:1 ggbs to quicklime might be appropriate. Higher ratios up to 6:1, are possible and will give even greater sulfate-resistance. There is insufficient data to recommend ratios greater than 6:1.

6. ORDER AND TIMINGS OF THE LIME AND GGBS APPLICATIONS

For non-cohesive sols, the lime does not have to be added before the ggbs. Fulton [6] reports that for soil stabilisation, the ggbs can be mixed with the untreated soil and left for one or two weeks before the lime is added. This sequence is used in the drilling of oil wells. For 'mud-to-cement-conversion' ggbs is mixed with the drilling mud and does not affect its properties even after 650 hours at 65^{o}C [36]. When drilling is finished, an alkaline activator is added down the drilling pipe and this converts the drilling mud into a cementitious seal.

Simultaneous application of the lime+ggbs is the normal practice in Australia, where the lime and ggbs are normally pre-blended [7,8].

An initial application of lime, with a delay before application of ggbs, is appropriate for cohesive soils. The initial application of lime modifies the soil and reduces its cohesiveness, which could otherwise interfere with the intimate mixing-in of the ggbs. Graham [37] suggests that this sequence is necessary when the plasticity Index of the soil exceeds '14'. Lime improvement has an almost immediate modifying effect with significant improvement on mixing and some remaining improvement occurring up to 72 hours later [2]. The Highways Agency specifies a period of between 24 and 72 hours of 'mellowing for normal lime-only stabilisation [2]. For lime+ggbs, Graham suggests the delay may be as short as 12 hours [37]. It would appear that the exact length of the delay is not critical. Wild et al [38] investigated the effect of a prolonged delay (7 days at 30^{o}C), between addition of lime and ggbs. They found that the delay did not have an adverse effect on the resistance to sulfate-induced swelling, if anything the reverse was the case.

Following addition of the ggbs, there is an extended period available for compaction and finishing. Samples stabilised with lime+ggbs showed no loss of strength with 12 hours delay between addition of ggbs and compaction [7]. South African Regulations permit up to 48 hours delay between addition of ggbs and the completion of compaction and finishing [5].

7. CONCLUSIONS

- Considerable oxidation of sulfide to sulfate was detected in laboratory studies of clays containing sulfide and similarly in a full-scale trial where the clay contained sulfide. Under the conditions of elevated pH that are produced by addition of lime or cement, the oxidation of sulfide to sulfate appears to take place very rapidly, within a time-scale of days. This oxidation can give rise to sulfate-related expansion effects in stabilised clays containing sulfide. This suggests that it would be prudent when assessing the suitability of soils for stabilisation, to measure their sulfide content as well as their sulfate content and assume that the sulfide is available for conversion to sulfate.
- Stabilisation with lime+ggbs, effectively combats the expansion associated with the presence of sulfate in soil and equally combats expansion associated with sulfides such as pyrites.
- Where ggbs is being used for enhanced resistance to sulfate expansion, the proportion of ggbs should at least equal that of the quicklime and typically for high resistance to sulfate expansion, a ggbs:quicklime ratio of 3:1, or even higher, may be appropriate.
- Lime+ggbs stabilisation offers other advantages for soil stabilisation:

  - A slower early-rate of strength development gives considerably more time for construction operations. South African Regulations permit up to 48 hours between the start and completion of stabilisation operations when lime/ggbs is used.
  - There is also extra ability to self-heal, in the case of early-life damage caused by overloading
  - In the long-term, there is an increased strength that will improve the structural performance.

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APPENDIX 1

Production and use of ggbs

Ground granulated blastfurnace slag (ggbs) is a by-product from the blast-furnaces used to make iron. These operate at a temperature of about 1500^{o}C and are fed with a carefully controlled mixture of iron-ore, coke and limestone. The iron ore is reduced to iron and the remaining materials form a slag that floats on top of the iron. This slag is periodically tapped off as a molten liquid and if it is to be used for the manufacture of ggbs it has to be rapidly quenched in large volumes of water. The quenching optimises the cementitious properties and produces granules similar to a coarse sand. This 'granulated' slag is then dried and ground to a fine powder in sophisticated production facilities, capable of processing up to half a million tonnes annually, to tightly controlled fineness.

The ggbs powder is a very-slow setting cement in its own right but, for most practical purposes, it needs to be activated and accelerated by alkali. The major use of ggbs is in the Construction Industry as a replacement for part of the cement content of concrete. For concrete, Portland cement is the normal activator and typically a combination of 50% ggbs with 50% Portland cement is used, but the proportions can be altered to optimise the technical properties of the concrete, according to the application. For example, where chemical resistance is called for, high proportions of ggbs (e.g. 70%) are used; conversely, where early strength is critical, the proportion of ggbs may be only 25%.

Research and long-term experience have demonstrated that concrete made with ggbs shows many advantages. Of particular note are:

- better workability,
- reduced early-age temperature rise
- resistance to alkali-silica reaction,
- resistance to chloride ingress
- resistance to sulphate attack.

Ggbs has environmental benefits relative to lime or cement:

- Its raw material is a by-product,
- Its manufacture involves only a fraction of the energy use and CO_2 emissions, associated with cement or lime.

APPENDIX 2

Abstracts from selected papers

[15] **Soil Stabilisation using Lime-activated Ground Granulated Blastfurnace Slag**

Synopsis: Soil stabilisation with cement or lime, is a well established technique for use in highway or foundation construction. Extensive laboratory investigations and a full-scale trial have been carried out to evaluate the performance of ground granulated blastfurnace slag (ggbs) in combination with lime, for stabilising soils. This paper reports the results of laboratory tests for strength and swelling, and also describes the full-scale trial.

The applicability of lime / ggbs combinations has been demonstrated. In addition laboratory tests have shown a previously undemonstrated advantage where the incorporation of ggbs combats the deleterious swelling which can occur when sulphate-containing soils are stabilised with cement or lime.

[20] **Mechanisms by which ggbs prevents sulfate attack of lime-stabilised kaolinite**

Abstract: This paper describes the mechanisms by which ggbs prevents sulfate-attack of lime-stabilised kaolinite. Microstructural and mineral phase analyses of compacted cylinders of lime-stabilised kaolinite with different percentages of lime replacement by ggbs have been carried out using scanning electron microscopy (SEM) and x-ray diffractometry (XRD). The cylinders were immersed in 4.2% Na_2S0_4 solution and also in deionised water for various time periods. The exposure data showed that the effect of ggbs in preventing the formation of expansive ettringite in lime-stabilised kaolinite, which had been exposed to 4.2% Na_2S0_4 solution was dramatic. The results also revealed three different growth mechanisms of ettringite in the lime-ggbs-kaolinite systems that were exposed to 4.2% Na_2S0_4 solution. These are: well-formed randomly orientated rods of high aspect ratio growing in pores and cracks, short needles covering surfaces of existing particles, and 'flower-like' needles radiating from isolated points and scattered randomly through the sample.

[19] **Influence of ggbs on the sulphate resistance of lime-stabilised kaolinite** (specimens immersed in sulfate solution, rather than sulfate in the clay)

Abstract: This paper describes the influence of ground granulated blastfurnace slag (GGBS) on the durability of lime-stabilised kaolinite in 4.2% Na_2S0_4 solution. Sulphate durability was assessed in the laboratory by means of linear expansion measurements, microstructure and mineral phase analysis of compacted cylinders of the lime-stabilised kaolinite with different percentages of' lime replacement by GGBS. The cylinders were immersed in 4.2% Na_2S0_4 solution and also in deionized water for various time periods. The exposure test data showed that the effect of GGBS on reducing expansion in 4.2% Na_2S0_4 Solution is dramatic. The results also showed that high percentages of replacement of lime with slag (in particular 83%), with just enough lime to activate the slag, were the most effective in preventing sulphate solution attack.

[11] **Shear strength, permeability and porosity of Kimmeridge clay, stabilised with lime and ggbs**

ABSTRACT: Kimmeridge Clay, obtained from Blackbird Leys near Oxford, England, UK, was stabilised with a total binder content of 8 % at various slag/lime ratios. The samples were cured for 12 weeks, 24 weeks and 1 year at 10, 20 and 30 'C. The shear strength development was assessed in a series of undrained, unconsolidated triaxial tests, during which the pore water pressure was measured. The permeability of the saturated soil-lime-ggbs mixes was measured in a computer controlled triaxial cell. The samples were then examined for their porosity and pore size distribution in order to assess the involved mechanisms.

The results indicate that, in general, the shear strength increases with increasing slag/lime ratio, particularly when the soil is cured at elevated temperatures. Also permeability drops significantly with increasing slag/lime ratio and increasing curing period, whereas curing temperature has only a minor influence on permeability. The pore refinement is maximised at replacement ratios of between 4% slag

slag/4% lime and 6% slag/2% lime, denoted by the highest percentages of pores with a radius of < 0.05 um.

[18] **Pyrite oxidation, expansion of stabilised clay and the effect of ggbs**

ABSTRACT: Over the past 5 years, a major research programme has been carried out into the use of lime/ggbs for the stabilisation of soils. This paper reports on selected parts of that programme, which relate to the oxidation of pyrite (iron sulfide), and the potential expansive effect that oxidation of sulfide can produce in stabilised clays. Field and laboratory studies on stabilised pyrite-containing clay, detected considerable oxidation of sulfide to sulfate and this was accompanied by expansion. The use of ggbs was beneficial in combating the expansion. Although oxidation of sulfides in soils is normally slow, the rate was found to greatly increase with the elevation of pH that is produced by addition of lime or cement. It is concluded that the physical and chemical effects that are an inherent part of soil stabilisation (i.e. disturbance of the soil, and most importantly, the elevated pH) produce conditions very conducive to the oxidation of sulfides. Consequently it is recommended that, when assessing the suitability of soils for stabilisation, the sulfide content as well as the sulfate content should be measured and it should be assumed that the sulfide is available for conversion to sulfate.

[27] **Insitu stabilisation using ggbs**

The trial formed part of the construction of a distribution warehouse. The sub-base for concrete hardstanding was the insitu soil stabilised with 9% cement. For a test area of $500m^2$ in the lorry loading area, 2% lime+8% ggbs was used instead of cement. The stabilising contractor experienced no difficulty in carrying out the ggbs stabilisation. Satisfactory density and strength were achieved. At 7-days cube strengths for the ggbs area were typically $2N/mm^2$ compared with $3N/mm^2$ for the cement area. At 28-days the ggbs strengths had exceeded those for cement and by 90 days had attained $6N/mm^2$.

[29] **Lime+ground granulated blastfurnace slag stabilisation of boulder clay on the A421 Tingewick Bypass**

ABSTRACT: Soil stabilisation with cement and lime, is well-established for use in highway construction. Recent research has shown advantages in using lime+ggbs (ground granulated blastfurnace slag) for this application. In particular, when sulphates are present in the clay, there is a dramatic reduction in the potential for disruptive swelling. As part of the construction of the Tingewick Bypass, a temporary diversion was needed to carry the A421 traffic. This site contained a sulphate-containing boulder clay and the opportunity was taken to evaluate lime+ggbs stabilisation in the presence of sulphate. The temporary diversion comprised a sub-base of the boulder clay stabilised with lime+ggbs, which was overlaid with 130mm of bituminous surfacing. This report describes the construction and the comprehensive testing carried out on the temporary diversion, including a comparison of lime+ggbs with lime+cement. Using standard plant and techniques the contractor experienced no difficulties and satisfactory density and strengths were achieved. Because of delays with the main contract, the temporary diversion carried the full A421 traffic for just over a year, providing an extended performance test. The temporary diversion performed well over this period. No disruption attributable to sulphate expansion was observed on the lime+ggbs sections but there were indications of expansion at the end of a short lime+cement section.